WBD Raw Telemetry to Calibrated Values Conversion

This document describes the procedure for obtaining calibrated data values for the Cluster Wideband (WBD) Receiver raw telemetry values. The calibrations supplied here are first order calibrations, which are suitable for most data analysis purposes. The calibration method described here is used in the example software (CALIBRATE.C) that has been provided to the Cluster Active Archive (CAA) and which is available on the WBD website at http://www-pw.physics.uiowa.edu/cluster/dvd/. Please note that a more accurate calibration could be achieved by using frequency dependent tables as discussed in B(4).

A. Calibrated Time Series

The following equations are used to obtain a calibrated WBD time series, either electric or magnetic field depending on the antenna that has been selected:

$$E_{\frac{V}{m}} = \frac{(raw\ count - DC\ offset) * \sqrt{2}}{counts / Vrms * antenna\ length * 10^{G/20}} \qquad (1)$$

$$B_{nT} = \frac{(raw\ count - DC\ offset) * \sqrt{2} * 2}{counts / Vrms * 10^{G/20}} \qquad (2)$$

Below is an explanation of the terms and functions contained in these equations:

(1) First a snapshot consisting of 1090 raw WBD data samples (raw counts) is obtained. These data samples can be 8-bits (0-255 raw count), or 4-bits (0-15 raw count), or 1-bit in size (0-1 raw count). The following calibrations are specified for 8-bit samples, so the raw counts for the 4-bit samples should be shifted up 4 bits and the 1-bit samples should be shifted up 7 bits to produce 8-bit samples for any data size. There are a number of options for the lower bits after shifting up: zeroes can be left in those bit positions, or the shifted bits can be replicated in the lower bit positions, or random noise could be inserted into those bit positions. Since the values of the lower bits are not known, any of these options are valid.

(2) The DC offset is obtained by averaging the 1090 samples. This resulting DC offset is then subtracted from the 1090 samples because the receiver is an AC-coupled system and the DC-component (DC offset) is not related to any sensor measurement. For 8-bit data, the value of this DC offset is typically around 127.5 counts, but the actual value can vary and depends upon the space environment in which the measurement was made. Removing this DC offset is necessary for the next step in the calibration procedure.

(3) The proper counts-to-Volts-rms factor is now applied to the data. This is the

amplitude in counts of a sine wave in the middle of the passband which would be measured by the WBD receiver if a 1 Volt-rms signal were injected into the electric or magnetic differential amplifier and the WBD receiver had no gain amplifier turned on. The 1090 samples, which have been adjusted by the DC Offset, are all divided by this factor. Another way this is expressed is the decibels (dB) below a maximum amplitude sine wave; for 8-bit data, which can range from 0 through 255, this is the number of dBs below a sine wave of amplitude 127.5 counts and is referred to as dBmax. This factor depends upon the filter mode:

Translation Mode	Filter	counts/Vrms	dBmax
Baseband	9.5 kHz	52.5	-7.7
Baseband	19 kHz	51.0	-8.0
Baseband	77 kHz	55.5	-7.2
125 kHz	9.5 kHz	26.5	-13.6
125 kHz	19 kHz	27.0	-13.5
125 kHz	77 kHz	30.0	-12.6
250 kHz	9.5 kHz	27.0	-13.5
250 kHz	19 kHz	27.5	-13.3
250 kHz	77 kHz	30.0	-12.6
500 kHz	9.5 kHz	18.0	-17.0
500 kHz	19 kHz	18.0	-17.0
500 kHz	77 kHz	30.0	-12.6

(4) Next the WBD gain amplifier value must be divided out. The gain can vary from 0 dB through 75 dB in steps of 5 dB. If the gain is G, then the 1090 samples should all be divided by $10^{G/20}$.

NOTE: The next (5^{th}) step in the calibration process is different for the electric field than for the magnetic field.

(5_E) To obtain the magnitude of the electric field for the electric antennas (Equation 1), we must now divide by the effective antenna length, thus obtaining units of Volts-rms per meter. Here the effective antenna lengths are defined as the physical tip-to-tip lengths:

Ey	88.0 meters
Ez	88.0 meters

Please be aware that the effective antenna length may differ from the physical length in some regions of Cluster's orbit. See Beghin et al., **Modeling of Cluster's Electric Antennas in Space: Application to Plasma Diagnostics**, *Radio Science, 40*, RS6008, doi:10.1029/2005RS003264, Nov. 24, 2005.

(5_M) To obtain the magnitude of the magnetic field for the magnetic search coil antennas (Equation 2), we now apply the search coil transfer function of 1 Volt = 1 nT by dividing by 1 (in effect multiplying counts/V_{rms} by 1 to get counts/nT_{rms}**,** and also take into account a -6 dB gain factor in the magnetic sensor differential amplifiers by multiplying by 2, thus obtaining units of nT_{rms}

(6) Finally, we multiply both equations (1) and (2) by the square root of 2 in order to obtain peak field values, as opposed to rms (root mean square) values, because WBD is designed as an rms measurement device. The units of the electric field will be V/m peak and of the magnetic field will be nT peak.

At this point, we have a calibrated time series. For those who wish to obtain a calibrated spectrogram, the following steps should be completed.

B. Calibrated Spectrogram

(1) Complete steps A(1) through A(4) for the electric field and steps A(1) through A(5_M) for the magnetic field.

(2) Apply a Hanning window to the calibrated 1090 samples. For a Hanning window the coherent gain is 0.5 (see "Digital Filter Design Handbook" by Fred J. Taylor). Therefore the 1090 samples must be multiplied by 2. The coefficients for a Hanning window are H_i=0.5*(1-cos(2*Π*i/(1090-1))) for i=0, 1090-1.

(3) An FFT should be performed on the 1090 samples, ensuring that the FFT output is properly normalized. To check the normalization of a given FFT implementation, apply the FFT to a sine wave of amplitude A, and do the following: square the real and imaginary parts of each FFT coefficient, add each resulting pair and take the square root, then sum over all coefficients. The result should be equal to the amplitude A. Note that the normalization factors may be different for different FFT implementations. The phase information from the FFT is not useful, so the magnitudes can now be calculated by squaring the real and imaginary parts, summing them and taking the square root.

(4) Now the frequency-dependent adjustments can be made if frequency dependent calibration tables are available. The calibration table provided for the time series in Step A(3) above gives frequency-independent calibration factors. However, the WBD amplitude response is not necessarily constant across any of the WBD passbands, so frequency–dependent calibration adjustments may be helpful for some applications of WBD data. There are no plans to develop frequency dependent calibration tables at this time. The errors associated with using the frequency-independent calibration tables are small and exist primarily on the edges of the passbands. Frequency-dependent calibration adjustments will probably be of minimal benefit to most users of WBD data.

(5) Once these calibrations have been applied, we have meaningful geophysical units: at each FFT frequency we have for the electric antennas the voltage measured across the antenna dipoles, and for the magnetic sensors we have nanotesla. However, we must now divide the electric antenna measurements by the effective antenna length per Step A(5_E) above in order to have meaningful electric field units.

(6) Finally, to obtain spectral density, one must square the values obtained from Steps B(3) through B(5) and divide by the bandwidth, which depends upon the type of window function used before performing the FFT. If no window function is used, then the equivalent noise bandwidth is the FFT bin width, which is the sample frequency divided by the number of samples ($f_S/1090$). If the Hanning window suggested above is used, then the equivalent noise bandwidth is 1.5 times the FFT bin width (again see "Digital Filter Design Handbook" by Fred J. Taylor). This operation applies for both electric field and magnetic field spectral density units ($V_{rms}^2/m^2/Hz$ or nT_{rms}^2/Hz, respectively).